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Diameter increment and growth patterns for individual tree growing in Central Amazon, Brazil

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Abstract

Information on diameter increment and growth patterns for individual trees are important tools for forest management primarily to: (i) select tree species for logging; (ii) selecting tree species for protection; (iii) estimate cutting cycles and (iv) to prescribe silvicultural treatments. Most growth and yield studies in tropical moist forests have emphasized only the stand level instead of individual trees. This study dealt with the analysis of individual growth patterns for 272 trees distributed over two transects (East–West and North–South) measuring 20 m × 2500 m, which were stratified by plateau, slope and ‘‘baixio’’ (lowland areas near small streams), and tree diameter at breast height (DBH) classes ($10\,\text{cm} \leq \text{DBH} < 30\,\text{cm}$, $30\,\text{cm} \leq \text{DBH} < 50\,\text{cm}$ and $\text{DBH} \geq 50\,\text{cm}$). For each tree, a metal ‘‘dendrometer’’ band was fixed to the trunk and growth in circumference was measured with digital calipers. Measurements were carried out for 19 months, from June 1999 to December 2000; for this study, only 12 months of year 2000 were considered. Individual growth pattern varied significantly over time ($P = 0.00$), and slightly ($P = 0.08$) when the interaction months and DBH classes was included; on the other hand, the signal was very weak ($P = 0.25$) when topographical classes were added to the later interaction, and no signal at all ($P = 0.89$) when the interaction between months, diameter and topographical classes were analyzed. Mean annual diameter increment considering all 272 monitored trees was 1.64 ± 0.21 mm per year (95% CI), falling within the range estimated for the Brazilian Amazon region (1.4–2 mm per year).

Keywords: Forest management; Tropical rainforest; Vegetation structure

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1. Introduction

Forest management on sustained yield basis requires information about diameter increment and growth pattern for individual trees species in addition to those related to forest stand productivity. Because of the difficulties in measuring accurately total or even merchantable tree height of tropical trees, diameter at breast height (DBH) has become the most important variable for allometric equations. Also, diameter increment measurements have been used to examine the dynamics of natural forests as well as the land use changes (Lea et al., 1979; Day Jr., 1985; Conner and Day Jr., 1992).

According to Mohd (1988), DBH increment was the most important variable to fit hypothesized production models for Peninsular Malaysia mixed forests. In tropical forests, size attribute is always more important than age to describe the dynamics of natural forest (Enright and Ogden, 1979), especially because age is

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difficult to measure accurately (Chambers et al., 1998). Besides, DBH is very easy to measure in the field without the risk in introducing non-sampling errors.

DBH growth rates vary significantly between and within tree species, and also in relation to age, season and microclimatic conditions (Ferri, 1979). Usually, tropical tree species present different behavior under different conditions, even for the same species or same botanical families. DBH growth is not directly controlled by soil moisture, but by plant hydrological balance in addition to other factors, which is, in turn, regulated by intensities of water absorption and transpiration (Ferri, 1979).

Most growth and yield studies in tropical moist forests have emphasized only the ecosystem or forest stand level instead of individual tree growth patterns. Periodic annual increments (PAI) in timber volume for tropical forests found in forestry literature were 2–4 $m^3 ha^{-1}$ per year for different managed sites in Asia and Africa (Wadsworth, 1987; Leslie, 1987) and 5 $m^3 ha^{-1}$ per year in the Brazilian Amazon sites 10 years after selective logging (Silva et al., 1996; Higuchi et al., 1997). Existing information on individual tree growth patterns in tropical forests are usually for few species, and they are only used for comparison with those that are managed (Manokaran and Kochummen, 1993; Milton et al., 1994; Herwitz and Young, 1994; Condit et al., 1995; Silva et al., 1996; Poels et al., 1998; Finegan et al., 1999).

Usually, PAI rates are estimated using repeated measurements on fixed-area permanent sample plots. In temperate forests, metal dendrometers have been used successfully to monitor diameter growth since 1944 (Keeland and Sharitz, 1993). However, published information concerning the use of metal dendrometers in tropical moist forests is rare; only two sites in the Brazilian Amazon, Manaus and Tapajós National Forest, are using this method to measure diameter growth, but there have been no published reports.

Utilization of metal dendrometers have shown the following advantages compared with standard methods: (i) easy to install and to take measurements; (ii) low costs and (iii) no damages to the trunk and cambium (Keeland and Sharitz, 1993). On the other hand, the main disadvantage pointed out by Bower and Blocker (1966) and Cameron and Lea (1980) is that the first year of measurements tend to underestimate diameter growth. However, Keeland and Sharitz (1993) pointed out that diameter growth underestimation could be due to the lack of growth, mainly in regions where annual season is well defined.

More recently, high precision automated dendrometers have been introduced in temperate forests to evaluate the relationship between phenology and individual tree growth. Tabuchi and Takahashi (1998) reported their experience with a dendrometer, Hi-Fi type, installed in some caducous species in northern Japan; changes in circumference were measured every hour during the plant-growing season. This study was carried out from April to August; individual diameter growth patterns were described well in relation to water availability and other environmental variables.

To combine production and conservation in tropical moist forests, it is necessary to understand natural forest dynamics and their internal growth and development mechanisms. In case of forest management on sustained yield basis, this understanding is important for making decisions such as (i) selecting tree species for logging, (ii) identifying tree species for protection, (iii) estimating cutting cycles and (iv) prescribing silvicultural treatments. The main objective of this study was to estimate annual diameter increment and to analyze growth patterns of tree species growing in two different topographical sequences in relation to monthly rainfall.

2. Study site and procedures

This study was carried out in the ZF-2 Experimental Station of the National Institute for Research in the Amazon (INPA), some 90 km North of Manaus, the capital of Amazonas State, Brazil. We used two transect plots established in 1996 by Jacaranda Project (agreement between INPA and Japan International Cooperation Agency, JICA). These transects measure 20 m × 2500 m (5 ha) each, oriented in East–West (E–W) and North–South (N–S) directions, and are stratified by plateau, slope and "baixio" (lowland areas associated with small streams). Vegetation structure (Higuchi et al., 1998) and soil studies (Ferraz et al., 1998) have been previously published for the same area.

Dense "terra-firme" tropical moist forest, which dominates Central Amazon landscape (Higuchi et al., 1997) is the main vegetation of the study site. About 10 km east of the transect plots, an inventory study (DBH $\geq$ 25 cm) within an area of 96 ha recorded 14,922 individuals and identified 409 different tree species, 206 genera and 51 families. The most abundant species were castanha jarana (*Holopyxidium jarana* Ducke — Lecytidaceae), inharé (*Helicostylis podogyne* Ducke — Moraceae) and uxi (*Endopleura uchi* Cuatr. — Humiriaceae) (Higuchi et al., 1985).

According to Ferraz et al. (1998), soil classification and textures for plateaus, slopes and "baixios" are, respectively, Oxisols very clayey, Ultisols clayey sand and sandy clay, and Entisols very sandy. Within the two transects, soils present low fertility, high acidity, and high negative charges at depressions.

Initially, 300 tree individuals were selected at random from Jacaranda Project transect plots (Higuchi et al., 1998), equally distributed among topographical classes (plateau, slope and "baixio"), the E–W and N–S transects, and the diameter classes (10 cm $\leq$ DBH $<$ 30 cm, 30 cm $\leq$ DBH $<$ 50 cm and DBH $\geq$ 50 cm). Metal dendrometer bands were installed on each selected tree, which measured changes in stem diameter through return spring displacement. Displacement measurements were taken by a digital caliper with precision of 0.01 mm.

All metal dendrometers were installed in June 1999 when the first measurement was taken. Following measurements were taken monthly always between days 25 and 30. According to the literature, the first three measurements are within the adjustment period of the metal dendrometers, and therefore, should be discarded (Keeland and Sharitz, 1993). For this study, we used only 12 measurements taken in 2000, increasing the adjustment period from 3 to 7 months. In the last measurement used here (December 2000), the total number of individuals with metal dendrometers were 272, distributed as following: 143 and 129 trees, respectively, in transects E–W and N–S; 105, 76 and 91 trees in plateau, slope and "baixio" and 89, 101 and 82 trees in classes (10 cm $\leq$ DBH $<$ 30 cm, 30 cm $\leq$ DBH $<$ 50 cm and DBH $\geq$ 50 cm). Natural mortality rate for the studied period was 2%, which is a typical for Manaus region (Higuchi et al., 1997). In addition, some trees were excluded from analysis because problems with spring defects and infestation of insects.

The principal three questions of this study were as follows. (i) Is diameter growth pattern dependent on size classes? (ii) Is there difference between transects E–W and N–S in terms of diameter annual increment? (iii) Is there variation in DBH increment over time (rainfall changes)? The first two questions were answered using ordinary one-way and two-way ANOVAs. For the third question, as repeated measurements were involved, we used the von Ende (1993) approach to carry out ANOVA using time (12 months of 2000) as split plots. For this analysis, each DBH class was subdivided using 5 cm intervals; thus, we worked with 432 cells (12 DBH cells $\times$ three topographical classes $\times$ 12 months). We used Greenhouse–Geisser (G–G) and/or Huynh–Feldt (H–F) to adjust ordinary F-test. G–G is smaller than H–F, so generally G–G is the more conservative adjustment (von Ende, 1993).

3. Results

Annual rainfall for the period 1980–2000 was 2610 ± 124 mm ($P = 0.05$) at EMBRAPA experimental station some 50 km East of the study site (da Silva, 2001). In the study area, 2000 rainfall was 3491 mm falling far outside the 95% CI for the region, thus the studied period was an outlier in terms of rainfall. From the scientific point of view, this is very important for our analysis because extrapolation using only 2000 measurements is not representative.

Botanical families such as Sapotaceae, Lecythidaceae and Caesalpinioidae were the most abundant in our data set with the following contribution in terms of number of individuals: 16, 15 and 7%, respectively. These contributions are the same as for the whole transects, which included more than 6000 individuals (Higuchi et al., 1998). Thus, besides the representative proportionality in relation to transect orientation, topographical classes and DBH classes, we also representatively sampled the tree community.

The two-way ANOVA of two transects ($\text{E}-\text{W} = 143$ monitored trees and $\text{N}-\text{S} = 129$ trees), three DBH classes ($\text{D1} = 89$ monitored trees, $\text{D2} = 101$ trees and $\text{D3} = 82$ trees) and three topographical classes (baixio = 91 trees, slope = 76 and plateau = 105) is presented in Table 1. With respect to mean monthly increment (MMI) in diameter, no statistical differences (ANOVA, $P = 0.433$) were found

Table 1
Between- and within-transects variation in terms of mean monthly DBH increment — ANOVA

Source of variation	SS	d.f.	MS	F-ratio	P
Between-transects	0.00188	1	0.00188	0.65937	0.43260
Within-transects (CT)	0.00054	2	0.00027	0.09477	0.91026
Transects × CT	0.00163	2	0.00081	0.28617	0.75612
Error	0.03417	12	0.00285	–	–

between the two transects, that is, we saw no variation between E–W (longitudinal) and N–S (latitudinal) orientations. It was also clear that there was no difference within-transects ($P = 0.91$), and plateau, slope and ‘‘baixio’’ had statistically the same MMI in diameter. Based on soil order and texture, we expected that growth patterns would be the same for both transects, but not within them because each topographical class has distinct soil types (Ferraz et al., 1998).

The repeated-measures ANOVA is presented in Table 2. As G–G was smaller than H–F epsilon (ε), we chose G–G to make inferences about the null hypothesis. Thus, only the MMI variation over time is highly significant ($P = 0.000$), and MMI did vary over time. As expected, MMI is smaller during the dry season (May–October). Graphically, this pattern can be observed in Fig. 1. However, during 2000, correlation analysis ($r = 0.40$) showed that MMI and precipitation correlated positively, but not significantly ($P = 0.20$). When we used mean monthly precipitation of 1980–2000 EMBRAPA data (da Silva, 2001), the correlation changed to $r = 0.84$ ($P = 0.001$). MMI does vary over time, but rainfall per se did not explain these differences in 2000.

The interaction of time × DBH classes was only significant at a critical level of 10% ($P = 0.079$). Thus, there was little evidence to support that MMI varies according to DBH classes over time. Also, there was no evidence ($P = 0.886$) that a time× topographical classes interaction exists. Using classical critical levels (1 and 5%), we found that time × topography × diameter interaction was not statistically significant.

The one-way ANOVA for three diameter classes and eight replications is presented in Table 3. There is good evidence that at least one DBH class is different (ANOVA, $P = 0.03$). Multiple comparisons for diameter classes showed that mean annual increment for the largest DBH class (DBH $\geq$ 50 cm) was significantly greater (Tukey, $P = 0.03$) than the other two classes. Supporting our findings, Clark and Clark (1999) concluded that growth pattern in diameter is highly dependent on tree size. Also, according to Hubbell et al. (1999), larger trees occupy the canopy,

Table 2
Repeated-measures ANOVA of split-plot design[a]

Source of variation	d.f.	SS	MS	F-ratio	P	G–G	H–F
(a) Between-subjects							
Topography (CT)	2	0.064	0.032	0.053	0.949		
Diameter (CD)	2	3.258	1.629	2.690	0.086		
CT × CD	4	0.180	0.045	0.074	0.989		
Error	27	16.352	0.606				
(b) Within-subjects							
Time (month)	11	11.675	1.061	19.306	0.000	0.000	0.000
Time × CT	22	0.573	0.026	0.473	0.980	0.886	0.940
Time × CD	22	2.166	0.098	1.791	0.017	0.079	0.040
Time × CT × CD	44	2.991	0.068	1.237	0.157	0.246	0.200
Error	297	16.328	0.055				

[a] G–G: Greenhouse–Geisser $\varepsilon = 0.398$; H–F: Huynh–Feldt $\varepsilon = 0.25$.

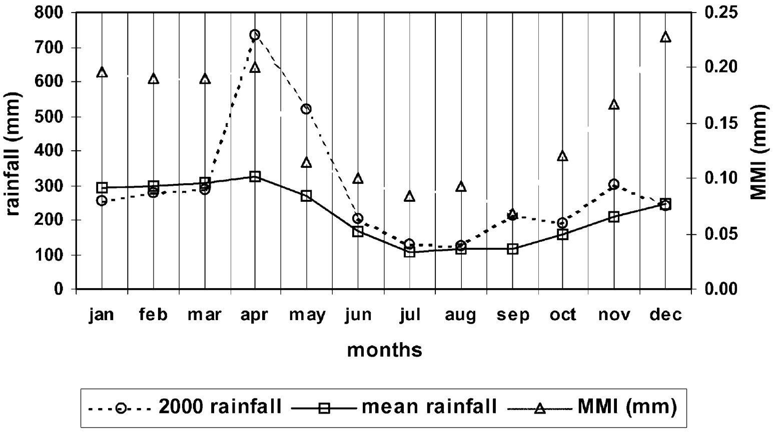

Fig. 1. Mean monthly increment (MMI in mm) in diameter in relation to the annual ZF-2 rainfall and the mean regional rainfall (1980–2000).

and have more energy supply and higher photosynthetic rates.

Mean annual diameter increment considering all 272 monitored trees was 1.64 ± 0.21 mm per year ($P = 0.05$), with minimum and maximum varying from -0.48 to 11.41 mm. This estimate fall within the range for the Brazilian Amazon, which varies from 1.4 mm per year obtained in Jari region (Gomide, 1997) to 2.0 mm per year in Tapajós National Forest (Silva et al., 1996). Also, our range (-0.48 to 11.41 mm) is comparable to those obtained in other tropical sites, such as 0.4–4.5 mm per year in Peninsular Malaysia (Manokaran and Kochummen, 1993), 5–18 mm per year in La Selva, Costa Rica (Clark and Clark, 1999), 7.1–9.2 mm per year in Barro Colorado, Panama (Condit et al., 1995).

The lowest and highest increments were obtained by maueira (*Erisma bicolor* Ducke, Vochysiaceae) and louro-fofo (*Ocotea immersa* van der Werff, Lauraceae), respectively. From the 272 trees with metal dendrometers, 42 (9 commercial species and 33 non-commercial) presented zero increment; 117 (45 commercial) presented mean increment equal to 0.64 mm per year, 69 (25 commercial) mean increment equal to 2.23 mm per year, and 44 (21 commercial species) presented mean annual increment equal to 4.77 mm per year.

Table 3
One-way ANOVA — variation between DBH classes

Source of variation	SS	d.f.	MS	*F*-ratio	*P*
DBH classes	0.03826	2	0.01913	4.16743	0.02991
Error	0.09640	21	0.00549		

Variation within species based on coefficient of variation (CV) was very high from 38% for cupiúba (*Goupia glabra* Aubl.) to 431% for seringa vermelha (*Hevea guianensis* Aubl.). In the first case, silvicultural treatments to favor growth will be useless because that species shows a strong inelasticity, and its development is not dependent on its spatial distribution or botanical association. On the contrary, *Hevea* shows a strong elasticity in terms of increment, and silvicultural treatments could favor its growth. Mean annual diameter increment for commercial species such as matamata (*Eschweilera coriacea* (DC.) Mart. ex Berg.), breu (*Protium altsonii* Sandwith), cardeiro (*Scleronema micranthum* Ducke) and ucuuba (*Virola calophylla* Warb.) were 2.3, 1.8, 2.1, 2.4 mm per year with reasonable elasticity (CVs varying from 66 to 89%); and prescription of silvicultural treatments over these species could be effective.

4. Conclusions

Metal dendrometers are useful and precise to monitor individual tree growth in diameter or changes of forest stand biomass or volume in the Brazilian Amazon forests. This approach can provide reliable information of the real world, which is needed to feed statistical models of forest dynamics modeling and simulation. Measurement reliability depends on the stem form, species phenology and infestation of climbers or insects (e.g. termites) on the stem. The limitation of the metal dendrometers used here is that they cannot measure expansion in diameter over 20 mm. Individuals that reach this limit in less than 1 year must change dendrometers, with a waiting period of at least 3 months for adjustment of dendrometer to the stem. So, change should be done 3 months early.

During the last 20 years, the mean annual rainfall was 2.610 ± 124 mm (95% CI) in an experimental station nor far from the study area. In 2000, accumulated rainfall collected in the study area was 3.491 mm. This means that our study period covered a rare year in terms of rainfall.

Mean monthly diameter increment varied considerably (repeated-measures ANOVA, $P = 0.000$) over time demonstrating that the greater the value of rainfall, the greater the increment. Also, there was a clear, but not very strong signal ($P = 0.079$) that a time × diameter classes interaction exists, and over time (rainfall changes) trees in higher classes (DBH ≥ 50 cm) tend to have greater increment in comparison with those of the two other classes. However, the signal of the interaction time × topography and diameter was very weak ($P = 0.246$), i.e. it is difficult to distinguish the transect influence on the individual tree growth over time. Finally, interaction time × topographical classes does not exist, demonstrating that individual growth pattern is the same on plateau, slope and "baixio" over time at least in a very wet year.

Mean annual diameter increment of 272 monitored trees of this study was 1.64 ± 0.21 mm (95% CI), falling within the range for Amazonian forests (1.4–2.0 mm per year).

Some species considered as commercial by INPA experimental forest management project such as tachi vermelho (*Sclerolobium setiferum* Ducke), sucupira chorona (*Andira micrantha* Ducke), guariúba (*Clarisia racemosa* Ruiz and Pav.), matamata amarelo (*Eschweilera coriacea* (DC.) Mart. ex Berg.) and angelim rajado (*Zygia racemosa* (Ducke) Barneby and J.W. Grimes) presented annual increment in diameter equal to 0. On the other hand, many commercial species presented annual increments above the Amazonian average, such as tanimbuca (*Buchenavia parvifolia* Ducke), pau-marfim (*Aspidosperma desmanthum* Müll. Arg.), cardeiro (*Scleronema micranthum* Ducke), cumaru (*Dipteryx odorata* (Aubl.) Wild.), angelim pedra (*Dinizia excelsa* Ducke), marupa (*Simarouba amara* Aubl.), tachi vermelho, morototo (*Schefflera umbrosa* Frodin) and two individuals of matamata and two of louro-fofo (*Ocotea aciphylla* (Nees) Mez). Mean annual increments for these varied from 5.28 to 11.41 mm per year, which are even greater than the average of managed tree species in Manaus (BIONTE site) and in Tapajós that is below 4 mm per year.

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